

# Three particle decays of light nuclei resonances

R Álvarez-Rodríguez<sup>1</sup>, A S Jensen<sup>2</sup>, E Garrido<sup>3</sup>,  
D V Fedorov<sup>2</sup>

<sup>1</sup> Departamento de Física e Instalaciones, ETS Arquitectura, Universidad Politécnica de Madrid, E-28040 Madrid, Spain

<sup>2</sup> Department of Physics and Astronomy, University of Aarhus DK-8000 Aarhus C, Denmark

<sup>3</sup> Instituto de Estructura de la Materia, Consejo Superior de Investigaciones Científicas E-28006 Madrid, Spain

E-mail: raquel.alvarez@upm.es

**Abstract.** We have studied the three-particle decay of  $^{12}\text{C}$ ,  $^9\text{Be}$  and  $^6\text{Be}$  resonances. These nuclei have been described as three-body systems by means of the complex scaled hyperspherical adiabatic expansion method. The short-distance part of the wave-function is responsible for the energies whereas the information related to the observable decay properties is contained at large distances, which must be computed accurately. As an illustration we show the results for the angular distribution of  $^9\text{Be}$  and  $^6\text{Be}$  resonances.

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## 1. Introduction.

In Quantum Mechanics the decay of two fragments is well determined by energy and momentum conservation laws. But the decay of three particles is a much more complicated issue. The energies of the decaying fragments are not fixed. The energy distribution of the three-body final state after the decay is an observable, and can be used to understand the structure of the initial state and the decay mechanism itself. On the other hand, the intermediate path connecting the initial and final states is not an observable. The only way to extract information about the decay mechanism is to try to understand the measurable final state by means of theoretical models. The decay is usually interpreted as either sequential via an intermediate configuration or direct to the continuum. The interpretations are often used to derive reaction rates for the inverse process in astrophysical environments. It is therefore important to have a reliable interpretation of the data.

We have focused our attention on three-body decaying nuclei involved in stellar nucleosynthesis reactions,  $^{12}\text{C}$ ,  $^9\text{Be}$  and  $^6\text{Be}$ . For all three there are experimental data available that help us to test the validity of our theoretical model.

## 2. Theoretical framework.

The three-body decaying nuclei are described as three-body systems within the complex-scaled hyperspherical adiabatic expansion method [1]. According to this method, The angular part of the Hamiltonian is first solved keeping fixed the value of the hyperradius  $\rho$ . Its eigenvalues serve as effective potentials while the eigenfunctions,  $\Phi_{nJM}$  are used as a basis to expand the total wave-function  $\Psi^{JM} = \frac{1}{\rho^{5/2}} \sum_n f_n(\rho) \Phi_{nJM}(\rho, \Omega)$ . The  $\rho$ -dependent expansion coefficients,  $f_n(\rho)$ , are the hyperradial wave functions obtained from the coupled set of hyperradial equations.

$^{12}\text{C}$  is described as three  $\alpha$ -particles,  $^9\text{Be}$  as two  $\alpha$ -particles and one neutron, and  $^6\text{Be}$  as one  $\alpha$ -particle and two protons. Our Hamiltonian contains short-range and Coulomb potential (between charged particles). We have considered  $\alpha - \alpha$  potential from [2],  $\alpha$ -nucleon from [3] and nucleon-nucleon from [4]. These potentials have been built in order to reproduce the two-body scattering data. On top of these interactions we include a structureless three-body potential of the form  $V_{3b} = S \exp(-\rho^2/b^2)$ , fitted to reproduce the resonance energies. This potential is included because at short distances the structure of these nuclei is not necessarily of three-body character. The complex scaling method helps us to treat the resonances as if they were bound states.

The many-body initial state resonance evolves into three clusters at large distances. The total angular momentum and parity  $J^\pi$  is conserved in the process. This symmetry imposes constraints on the resulting momentum distributions. The energy distribution is the probability for finding a given particle at a given energy. It can be measured experimentally and is the only information that allows us to study the decay path, that can be either sequential or direct or a mixture. The information about the energy distributions of the fragments after the decay is contained in the large-distance part of the wave-function, which must be accurately computed. The single particle probability distributions are obtained after Monte Carlo integration of the absolute square of the large-distance wave-function.

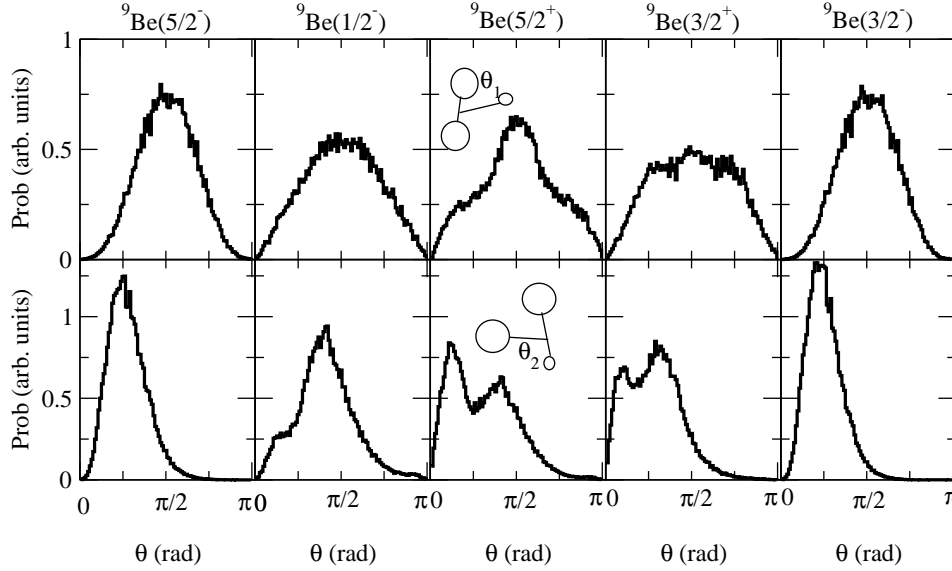
## 3. Results.

### 3.1. $^{12}\text{C}$

Within this theoretical framework we have extensively studied the decay of the low-lying  $^{12}\text{C}$  resonances [5]. Our results have been compared to recent experimental data [6] with a high level of agreement. Moreover, our suggestion to change the previously assigned spin and parity of the 13.35 MeV state [7] from  $2^-$  to  $4^-$  has been supported by the experimental community [6, 8].

### 3.2. $^9\text{Be}$

We have studied the five lowest resonances of  $^9\text{Be}$  [9] and compared them to the experimental data from [10]. Fig. 1 shows the angular distributions of these resonances, *i.e.* the probability for finding one of the decaying particles in a certain direction with respect to the direction formed by the other two. In all the cases we have removed the sequential decay via  $^8\text{Be}(0^+)$ . This kind of plot contains information about the angular momentum of the first particle relative to the centre-of-mass of the other two. We observe that the angular distribution patterns are different for different  $J^\pi$  states. These features are clearly distinguishable, demonstrating that these observables can be used to determine the large-distance structure of these resonances. The initial state



**Figure 1.** The angular distributions of the directions between two particles and their centre-of-mass and the third particle for the  $5/2^-$ ,  $1/2^-$ ,  $5/2^+$ ,  $3/2^+$  and  $3/2^-$  resonances of  ${}^9\text{Be}$  as labelled in the figure. The distributions have been computed for the two possible angles that can be defined in our three-body system.

can still be determined only through the theoretical information about the dynamical evolution of the resonances.

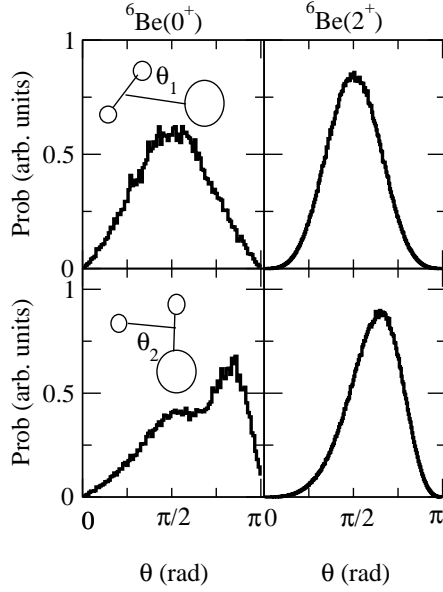
### 3.3. ${}^6\text{Be}$

The  ${}^6\text{Be}$  is an unbound nucleus which has only two low-lying resonances,  $0^+$  and  $2^+$ . Its decay has been recently measured [11] and compared to theoretical predictions given by our formalism. We have not found any signatures of sequential decay of these resonances via intermediate two-body states. We show in fig. 2 the angular distributions for the two resonances of  ${}^6\text{Be}$ . The upper panels can be compared directly to the experimental data from [11]. They show that the  $\alpha$ -particle prefers to come out perpendicular to the direction formed by the two protons.

## 4. Summary and Conclusions.

We have applied a general method to compute the momentum distributions of three-body decaying light-nuclei resonances. We have conjectured that the energy distributions of the decay fragments are insensitive to the initial many-body structure. The energy distributions are then determined by the energy and three-body resonance structure as obtained in a three-body cluster model. These momentum distributions are determined by the coordinate space wave-functions at large distances, which much be computed with a high accuracy.

The method has been applied previously to the study of the decay of  ${}^{12}\text{C}$  resonances with great success. In this contribution we have shown the angular



**Figure 2.** Same as in fig. 1, but for the  $0^+$  and  $2^+$  resonances of  ${}^6\text{Be}$ .

distribution of the low-lying  ${}^9\text{Be}$  and  ${}^6\text{Be}$  resonances decaying into  $\alpha + \alpha + n$  and  $\alpha + p + p$  respectively. Our distributions are open to experimental tests.

### Acknowledgments

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